

# CP Asymmetries in Strange Baryon Decays

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While indirect & direct CP violations (CPV) had been established in the decays of strange & beauty mesons, none have been done for baryons. There are different "roads" for finding CP asymmetries in the decays of strange baryons; they are highly non-trivial ones. The HyperCP Collaboration had probed CPV in the decays of single  $\Xi$  &  $\Lambda$  [1]. We talk about future lessons from  $e^+e^-$  collisions at BESIII/BEPCII: probing decays of *pairs* of strange baryons, namely  $\Lambda$ ,  $\Sigma$  &  $\Xi$ . Realistic goals are to learn about non-perturbative QCD. One can hope to find CPV in the decays of strange baryons; one can also dream to find impact of New Dynamics (ND). We point out that a new important era starts with the BESIII/BEPCII data accumulated by the end of 2018.

## I. THE LANDSCAPE

CP violation (CPV) has been found in  $K_L \rightarrow \pi^+\pi^-$  in 1964 [2] (actually 'predicted' by L.B. Okun in 1963 [3]) and tiny *direct* CPV in differences  $K_L \rightarrow \pi^+\pi^-$  vs.  $K_L \rightarrow \pi^0\pi^0$  in 1990's by NA31/NA48 and KTeV. Present analyses give in Particle Data Group 2016 (PDG2016) [4]:

$$|\epsilon_K|_{\text{exp.}} = (2.228 \pm 0.011) \cdot 10^{-3},$$

$$\text{Re}(\epsilon'/\epsilon_K)_{\text{exp.}} = (1.66 \pm 0.23) \cdot 10^{-3}; \quad (1)$$

i.e., CPV in  $\Delta S = 1$  has been found there around the scale of  $5 \cdot 10^{-6}$ . The impact of New Dynamics (ND) can possibly hide in the uncertainties about *direct* CPV. It has been suggested that it might have been overstated what the Standard Model (SM) can produce here [5]. We have gotten the first result from the LQCD tool [6]:

$$\text{Re}(\epsilon'/\epsilon_K)_{\text{LQCD}} = (0.138 \pm 0.515 \pm 0.443) \cdot 10^{-3}. \quad (2)$$

Obviously we need more lattice data. So far, it is not clear which lesson we can find here: does it mean that these data are consistent what the SM gives us or it is a sign for the impact of ND?

Soon after 1964 it was said to probe CPV in the transitions of strange *baryons*. It is a huge challenge to find it. However, the goal is so important that we should not give up. Present experimental limits are high about what one can think about even the possible impact of the ND. In 1998 it had been described in several situations, in particular about CP observables in  $B^0(t) \rightarrow$  hyperon-antihyperon, where CPV could be found based on predictions at *that* time [7].

The landscape of fundamental dynamics have changed very much after the 2nd millennium. Neutrinos are massless in the SM; however neutrino oscillations have been established. The SM produces true large CP asymmetries

in  $\Delta B \neq 0$  transitions, and indeed the BABAR/Belle Collaborations have found in the beginning of the 3rd millennium with  $B^0 \rightarrow J/\psi K_S$  & others. Still no non-zero values of CP asymmetries have been established in the decays of baryons in general beyond the huge asymmetry in matter vs. anti-matter in our Universe (or our 'existence'). However, evidence has been seen by the LHCb experiment in  $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$  for regional CPV [8]. Obviously we are talking about direct CPV in  $\Delta B = 1$ . In two-body final states (FS) of beauty *mesons* the usual scale is  $\sim 0.1$ ; for  $\Lambda_b^0$  decays it suggests that a regional one is sizably enhanced. Can it happen also for strange baryons?

The final states (FS) are mostly produced by two-body ones in the decays of strange baryons. There are two classes of transitions as PDG2016 data give us:

- Re-scattering gives sizable impacts, and it is obvious for  $\Lambda$  and  $\Sigma^+$ :

$$\begin{aligned} \text{BR}(\Lambda \rightarrow p\pi^-) &= 0.639 \pm 0.005 \\ \text{BR}(\Lambda \rightarrow n\pi^0) &= 0.358 \pm 0.005 \\ \text{BR}(\Lambda \rightarrow p\pi^-\gamma) &= (8.4 \pm 1.4) \times 10^{-4} \\ \text{BR}(\Sigma^+ \rightarrow p\pi^0) &= 0.5157 \pm 0.0030 \\ \text{BR}(\Sigma^+ \rightarrow n\pi^+) &= 0.4831 \pm 0.0030 \end{aligned} \quad (3)$$

CPT invariance is 'usable' telling us about averaged asymmetries<sup>1</sup>. These widths are basically produced with two hadrons; thus:  $\Gamma(\Lambda \rightarrow p\pi^-) + \Gamma(\Lambda \rightarrow n\pi^0) \simeq \Gamma(\bar{\Lambda} \rightarrow \bar{p}\pi^+) + \Gamma(\bar{\Lambda} \rightarrow \bar{n}\pi^0)$ ; likewise for  $\Sigma^+$ . Therefore

$$A_{\text{CP}}(\Lambda \rightarrow p\pi^-) \simeq -A_{\text{CP}}(\Lambda \rightarrow n\pi^0) \quad (4)$$

$$A_{\text{CP}}(\Sigma^+ \rightarrow p\pi^0) \simeq -A_{\text{CP}}(\Sigma^+ \rightarrow n\pi^+) \quad (5)$$

The goal is to establish CP asymmetries in one two-body final states of  $\Lambda$  and also for  $\Sigma^+$ . Finding also in another decay is nice, but not important.

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<sup>1</sup> The impact of CPT invariance goes well beyond the same mass & width as discussed in [9].

When one discusses decays  $\Lambda \rightarrow p\pi^-$  without the spins of the baryons included, one gets only one observable, namely a number. The data depend on production asymmetries in  $\Lambda \rightarrow p\pi^-$  vs.  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ . That is not a problem for  $e^+e^-$  annihilations for the BESIII experiment or for  $\bar{p}p$  collisions; however the situation is quite different for  $pp$  ones from LHCb data.

- The situations are more complex: the impact of re-scattering is not obvious, when one cannot use polarized baryons, as one can see in the branching ratios:

$$\begin{aligned} \text{BR}(\Sigma^- \rightarrow n\pi^-) &= (99.848 \pm 0.005) \times 10^{-2} \\ \text{BR}(\Sigma^- \rightarrow n\pi^-\gamma) &= (4.6 \pm 0.6) \times 10^{-4} \\ \text{BR}(\Xi^0 \rightarrow \Lambda\pi^0) &= (99.524 \pm 0.012) \times 10^{-2} \\ \text{BR}(\Xi^0 \rightarrow \Lambda\gamma) &= (1.17 \pm 0.07) \times 10^{-3} \\ \text{BR}(\Xi^- \rightarrow \Lambda\pi^-) &= (99.887 \pm 0.035) \times 10^{-2} \\ \text{BR}(\Xi^- \rightarrow \Sigma^-\gamma) &= (1.27 \pm 0.23) \times 10^{-4} \end{aligned} \quad (6)$$

Probing CPV in strange baryons transitions is a true challenge to be successful. In the end of the previous millennium we got a predictions based on the SM [10, 11]:

$$\begin{aligned} A_{\text{CP}}(\Lambda \rightarrow p\pi^-) &\sim (0.05 - 1.2) \cdot 10^{-4} \quad (7) \\ A_{\text{CP}}(\Xi^- \rightarrow \Lambda\pi^-) &\sim (0.2 - 3.5) \cdot 10^{-4} \quad (8) \end{aligned}$$

In the beginning of this millennium we got a SM prediction by combining  $\Lambda$  &  $\Xi$  decays [12]:  $-0.5 \cdot 10^{-4} \leq A_{\Lambda\Xi} \equiv \frac{\alpha_{\Lambda\Xi} - \alpha_{\bar{\Lambda}\bar{\Xi}}}{\alpha_{\Lambda\Xi} + \alpha_{\bar{\Lambda}\bar{\Xi}}} \leq 0.5 \cdot 10^{-4}$ .

The HyperCP experiment <sup>2</sup> had searched for CPV by a 800 GeV proton beam on a Cu target [1]:

$$A_{\Lambda\Xi} = (0.0 \pm 5.1 \pm 4.4) \cdot 10^{-4}. \quad (9)$$

It is still not clear, whether the theoretical uncertainties are included correctly.

However, two points might help to reach our goals:

- The BESIII collaboration can probe *pairs* of strange baryons. We will discuss that in Sect.II.
- Future BESIII analyses will be enhanced, namely  $e^+e^- \rightarrow J/\psi$  with the unusual narrow resonance as a source of strange baryons from PDG2016:

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \bar{\Lambda}\Lambda) &= (1.61 \pm 0.15) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Lambda}\bar{\Lambda}\pi^+\pi^-) &= (4.3 \pm 1.0) \cdot 10^{-3} \end{aligned}$$

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \bar{\Lambda}pK^+/\bar{\Lambda}pK^-) &= (0.89 \pm 0.16) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Sigma}^+\Sigma^-/\bar{\Sigma}^-\Sigma^+) &= (1.50 \pm 0.24) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Xi}^0\Xi^0) &= (1.20 \pm 0.24) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{\Xi}^+\Xi^-/\bar{\Xi}^-\Xi^+) &= (0.86 \pm 0.11) \cdot 10^{-3} \quad (10) \end{aligned}$$

These rates are produced by strong forces, and they can be compared with

$$\begin{aligned} \text{BR}(J/\psi \rightarrow \bar{p}p) &= (2.120 \pm 0.029) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{p}p\pi^+\pi^-) &= (6.0 \pm 0.5) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow p\bar{n}\pi^-) &= (2.12 \pm 0.09) \cdot 10^{-3} \\ \text{BR}(J/\psi \rightarrow \bar{n}n) &= (2.09 \pm 0.16) \cdot 10^{-3} \end{aligned} \quad (11)$$

The final state interactions (FSI) show impact, although our ‘community’ is so far not able to describe it quantitatively.

We will discuss in some details what we can learn about fundamental dynamics including CP asymmetries. It is not trivial at all; as usual there is a price for a prize.

## II. CP ASYMMETRIES IN $J/\psi \rightarrow$ PAIR OF STRANGE BARYONS

Mostly we discuss the decays of  $J/\psi$  to final states with only two strange baryons. We also include special cases in Sect.IIF.

First we quickly go back to the history about discrete symmetries, in particular about “parity conservation, charge-conjugation invariance, and time-reversal invariance” in the decays of hyperons [13]. PDG2016 gives for the decay of  $\Lambda \rightarrow p\pi^-$  a T-odd moment  $\alpha_{\Lambda} = 0.642 \pm 0.013$ , while  $\alpha_{\bar{\Lambda}} = -0.71 \pm 0.08$  for  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ ; the dominant data come from the BES Collaboration:  $\alpha_{\bar{\Lambda}} = -0.755 \pm 0.083 \pm 0.063$  [14].

Published 2010 data from the BES Collaboration are based on  $5.8 \times 10^7$   $J/\psi$  events [14]; there we are talking about 10 % of the accuracy. To reach the level of  $\mathcal{O}(1\%)$  is not trivial. However, we discuss about the level of 0.1 % and pointed out that our community will have the data to reach that by 2018. We have to be realistic: this prize cannot be reached easily. On the other hand, it would be very pessimistic to suggest we will follow the ‘road’ of the Higgs boson, namely searching for 40 years.

Now it has already  $\simeq 1.3 \times 10^9$   $J/\psi$  events collected by the BESIII detector. It expects to get close to  $10^{10}$   $J/\psi$  events by the end of 2018 [15]. The situations are even more complex, when we discuss  $\text{BR}(J/\psi \rightarrow \bar{\Xi}\Xi \rightarrow [\bar{\Lambda}\pi][\Lambda\pi])$  in Sect.IIE.

### A. General statements about first steps

First we describe the ‘landscape’ and the tools one can use there. The super narrow vector resonance  $J/\psi$  produces a connection of the spins of a pair of hyperons  $Y$

<sup>2</sup> The authors of this proposal “HyperCP: Search for CP Violation in Charged-Hyperon Decays” quoted Bigi and Sanda from their recent book *CP Violation: “We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics.”*. At least one of the co-authors of this paper agrees.

of  $\Lambda$ ,  $\Sigma$  &  $\Xi$  and FS  $X$  of  $p$ ,  $\Lambda$ :

$$J/\psi \rightarrow \bar{Y}Y \rightarrow [\bar{X}\pi][X\pi] \quad (12)$$

One can measure  $T$ -odd moments:

$$\alpha_Y^{(X)} = \langle \vec{\sigma}_Y \cdot (\vec{\sigma}_X \times \vec{\pi}_X) \rangle, \quad \alpha_{\bar{Y}}^{(\bar{X})} = \langle \vec{\sigma}_{\bar{Y}} \cdot (\vec{\sigma}_{\bar{X}} \times \vec{\pi}_{\bar{X}}) \rangle, \quad (13)$$

where  $\vec{\sigma}$  &  $\vec{\pi}$  describe the spins & the momenta of the baryons in the rest frames of  $Y/\bar{Y}$ . It is not surprising to find sizable or even large non-zero values of  $T$ -odd moments; below we will give an example from data with actually large values. It shows the impact of FSI. Non-zero values of  $T$ -odd moments do *not* mean by themselves we have found  $T$  violation – or CP violation using CPT invariance. However, one can probe direct CP asymmetries

$$\langle A_{\text{CP}}^{(X)} \rangle = \frac{\alpha_Y^{(X)} + \alpha_{\bar{Y}}^{(\bar{X})}}{\alpha_Y^{(X)} - \alpha_{\bar{Y}}^{(\bar{X})}} \quad (14)$$

without polarized  $Y$  &  $\bar{Y}$ . The crucial point is to use the connection of the spin-1 of the initial state  $J/\psi$  with the FS with two spin-1/2. The crucial point is: the goal is to find  $\langle A_{\text{CP}}^{(X)} \rangle \neq 0$  without directly measuring polarization of  $Y/\bar{Y}$  &  $X/\bar{X}$  baryons and their correlations due to the very narrow resonance  $J/\psi$  in their production.

One goes to measure correlations between the pair of FS baryons & pions. In the rest frame of  $J/\psi$  one can define  $C_T = (\vec{p}_X \times \vec{p}_\pi) \cdot \vec{p}_{\bar{X}}$  & conjugate transitions  $\bar{C}_T = (\vec{p}_{\bar{X}} \times \vec{p}_{\bar{\pi}}) \cdot \vec{p}_X$  and compare the event numbers ( $N$ ) with positive and negative values

$$\langle A_T \rangle = \frac{N(C_T > 0) + N(C_T < 0)}{N(C_T > 0) - N(C_T < 0)} \quad (15)$$

$$\langle \bar{A}_T \rangle = \frac{N(\bar{C}_T > 0) + N(\bar{C}_T < 0)}{N(\bar{C}_T > 0) - N(\bar{C}_T < 0)}. \quad (16)$$

Thus

$$\mathcal{A}_T = \langle A_T \rangle + \langle \bar{A}_T \rangle \neq 0 \quad (17)$$

are observable CP asymmetries (based on CPT invariance).

The landscapes are quite different for  $\Lambda \rightarrow p\pi^-$  &  $\Sigma \rightarrow p\pi$  and even more with  $\Xi \rightarrow \Lambda\pi$  with many ‘roads’ for transitions as listed:  $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$ ;  $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$ ;  $J/\psi \rightarrow \bar{\Xi}^0\Xi^0 \rightarrow [\bar{\Lambda}\pi^0][\Lambda\pi^0]$ ;  $J/\psi \rightarrow \bar{\Xi}^+\Xi^- \rightarrow [\bar{\Lambda}\pi^+][\Lambda\pi^-]$ <sup>3</sup>.

- One can calibrate those transitions with  $J/\psi \rightarrow \Delta(1232)\bar{\Delta}(1232)$ , where CPV cannot appear there.

- That is not the end of the impact of strong resonances of  $\Delta(1232)$  with the width  $\sim 117$  MeV and  $N(1440)$  with the width  $250 - 450$  MeV. They will affect the lessons we learn from future data about possible CP violations in the transitions of strange baryons.
- The item of “duality” between the worlds of quarks vs. hadrons is very subtle, in particular close to thresholds of resonances.

Channel	# of events	Sensitivity on $\mathcal{A}_T$
$J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow [p\pi^-][\bar{p}\pi^+]$	$2.6 \times 10^6$	0.06%
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^- \rightarrow [p\pi^0][\bar{p}\pi^0]$	$2.5 \times 10^6$	0.06%
$J/\psi \rightarrow \Xi^0\bar{\Xi}^0 \rightarrow [\Lambda\pi^-][\bar{\Lambda}\pi^+]$	$1.1 \times 10^6$	0.1%
$J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow [\Lambda\pi^0][\bar{\Lambda}\pi^0]$	$1.6 \times 10^6$	0.08%

TABLE I. The number of reconstructed events after considering the decay branching fractions, tracking, particle identifications. The sensitivity is estimated without considering the possible background dilutions, which should be small at the BESIII experiment. Estimations are based on the  $10^{10}$   $J/\psi$  data which will be collected by BES collaboration at 2018 (& the branching fractions from PDG2016). Systematic uncertainties are expected to be at the same order as the statistical one shown in the table.

Here we estimate the sensitivities for measuring such observables using the collected  $J/\psi$  sample. In 2018  $10^{10}$   $J/\psi$  events will be accumulated by the BESIII experiment [15]. The detection efficiency for pion, proton, kaon with momentum larger than 100 MeV can reach 98%. As for particle identification (PID), the pion, kaon and proton can be distinguished with  $3\sigma$  (three standard deviation) below momentum of 1.0 GeV. Considering the branching fractions of  $J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow [p\pi^-][\bar{p}\pi^+]$  and  $J/\psi \rightarrow \Xi^0\bar{\Xi}^0 \rightarrow [\Lambda\pi^-][\bar{\Lambda}\pi^+]$  [4] etc., we can estimate the expected number of events and the further sensitivities, see Table I. Probing such large data with re-fined tools will give us information rich about the underlying dynamics.

## B. Going beyond first steps

Measuring  $\mathcal{A}_T$  is the first step to probe CP asymmetries. There are possible options for intermediate steps like:

$$A_T(d) = \frac{N(C_T > |d|) + N(C_T < -|d|)}{N(C_T > |d|) - N(C_T < -|d|)} \quad (18)$$

$$\bar{A}_T(d) = \frac{N(\bar{C}_T > |d|) + N(\bar{C}_T < -|d|)}{N(\bar{C}_T > |d|) - N(\bar{C}_T < -|d|)} \quad (19)$$

It is a very promising way to go beyond  $\mathcal{A}_T$ . By the end of 2018 we can expect that BESIII can probe CPV in the

<sup>3</sup>  $M(\Lambda) \simeq 1116$  MeV;  $M(\Sigma^+) \simeq 1189$  MeV;  $M(\Xi^0) \simeq 1315$  MeV;  $M(\Xi^-) \simeq 1322$  MeV.

decays of strange baryons on the level of  $10^{-4}$  sensitivity, see in Tab. I (neglecting the systematic errors).

The above method can be also applied to  $J/\psi \rightarrow \Lambda \bar{\Lambda} \pi \pi$  to probe the CPV in  $\Xi$  decay. Interestingly, for the case of  $\Xi$  baryon the CPV can be also probed by *polarized*  $\Xi$  thanks to the decay chain  $\Xi^0 \rightarrow \Lambda \pi \rightarrow (p\pi)\pi$  where the  $CP$  violating observable can be related to the helicity amplitudes, see a similar proposal in Ref. [16] for  $\Lambda_c$  decay. Such  $CP$  violating signal can be extracted by performing an angular analysis which is again accessible in the BESIII experiment due to the large  $J/\psi$  data. However, for  $\Lambda$  decays the interference of the helicity amplitude is absent in the angular observable [14], which handicaps accessing  $CP$  as the same way in polarized  $\Xi$  decay, i.e., measuring the interference of helicity amplitudes.

### C. $J/\psi \rightarrow \bar{\Lambda} \Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$

The DM2 Collaboration had measured  $CP$  invariance (and Quantum Mechanics) in  $e^+e^- \rightarrow J/\psi \rightarrow \bar{\Lambda} \Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$  in 1988 without polarized  $\Lambda$  &  $\bar{\Lambda}$ ; their result  $A_{CP} = 0.01 \pm 0.10$  [17]. It is the first step in an important direction.

Now we describe the situation 30 years later, say the potential what BES can achieve by 2018. We use the Jacob-Wick helicity formalism [18], as one can see in the Fig.3 of the Ref.[14]; it was also applied in the Refs.[19, 20]:

- The  $J/\psi$  rest frame is along the  $\Lambda$  out-going direction, and the solid angle  $\Omega_0(\theta, \phi)$  is between the incoming  $e^+$  & out-going  $\Lambda$ .
- For  $\Lambda \rightarrow p\pi^-$  the solid angle of the ‘daughter’ particle  $\Omega_1(\theta_1, \phi_1)$  is referred to the  $\Lambda$  rest frame (although as out-going direction); likewise for  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ .

We describe the angular distribution for this process following Ref.[21]:

$$\begin{aligned} \frac{d\Gamma}{d\Omega} \propto (1 - \alpha) \sin^2 \theta \cdot \left[ 1 + \alpha_\Lambda \alpha_{\bar{\Lambda}} (\cos \theta_1 \cos \bar{\theta}_1 \right. \\ \left. + \sin \theta_1 \sin \bar{\theta}_1 \cos(\phi_1 + \bar{\phi}_1)) \right] \\ - (1 + \alpha)(1 + \cos^2 \theta) (\alpha_\Lambda \alpha_{\bar{\Lambda}} \cos \theta_1 \cos \bar{\theta}_1 - 1) , \end{aligned} \quad (20)$$

where  $d\Omega \equiv d\Omega_0 d\Omega_1 d\bar{\Omega}_1$  and:

- $\alpha$  is the angular distribution parameter for  $\Lambda$ ;
- $\alpha_\Lambda [\alpha_{\bar{\Lambda}}]$  is the  $\Lambda [\bar{\Lambda}]$  decay parameter;
- these data depend only on the product of  $\alpha_\Lambda \alpha_{\bar{\Lambda}}$ , see Eq.(20).

By fitting Eq. (20) to the data, one can determine  $\alpha_{J/\psi}$  and  $\alpha_\Lambda \alpha_{\bar{\Lambda}}$ . One can make a replacement:

$$\alpha_\Lambda \alpha_{\bar{\Lambda}} \equiv \frac{A - 1}{A + 1} \alpha_\Lambda^2 , \quad (21)$$

where  $A$  describes a  $CP$  asymmetry observable.

As said before published 2010 data from the BES collaboration show [14]  $\alpha_{\bar{\Lambda}}^{(\bar{p})} = -0.755 \pm 0.083 \pm 0.063$  based on previously measured  $\alpha_\Lambda^{(p)} = 0.642 \pm 0.013$ . Their non-zero numbers show the impact of re-scattering; it is large, which is not surprising. We also note that Eq. (20) is derived from considering only spin projection  $J_z = \pm 1$  for  $J/\psi$ , which is a consequence of QED process:  $e^+e^- \rightarrow \gamma \rightarrow c\bar{c}$  ( $J/\psi$ ) [22]. Thus only the product term  $\alpha_\Lambda \alpha_{\bar{\Lambda}}$  can be measured<sup>4</sup>.

Present limit on direct  $CP$  asymmetry is around a few percent; hardly even ND cannot produce effects close to 1% here. To reach the  $\mathcal{O}(0.1\%)$  would be a sizeable achievement about  $\langle A_{CP} \rangle$  based on  $\alpha_\Lambda^{(p)} \sim \alpha_{\bar{\Lambda}}^{(\bar{p})} \sim 0.64$ . Measuring semi-local asymmetry would give us new lessons about non-perturbative QCD.

It has been said very recently in the Ref. [23] that the Ref. [14] missed some contributions for *on-shell*  $J/\psi \rightarrow \bar{\Lambda} \Lambda \rightarrow \bar{p}\pi^+ p\pi^-$ ; so far we are not convinced. Of course, experimental data from the BESIII are needed in order to test it.

Even now BESIII has many more data, and by 2018 we will have about  $2.6 \times 10^6$  events for  $J/\psi \rightarrow \bar{\Lambda} \Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$  decay chain after considering the efficiencies for tracking, particle identification and  $\Lambda$  pair reconstruction [15]. The sensitivity might reach  $6 \times 10^{-4}$  by 2018 as listed in Table I. Now the landscape is different with some hope to find  $CP$  asymmetry here, and also for  $J/\psi \rightarrow \bar{\Sigma} \Sigma$  that will be discussed below.

General items: (a) Except  $n - \bar{n}$  (or maybe, maybe even  $\Lambda - \bar{\Lambda}$ ) oscillations [25] one probes only direct CPV with baryons. (b) It is well-known that the impact (local) penguin operators are crucial for  $\Delta S = 1$  transitions for strange mesons, in particular about non-zero value for  $\epsilon'$ . What about decays of strange baryons? The transitions of a pair of strange baryons are not far from thresholds; thus one has to think about the item of “duality” between the worlds of hadrons and quarks & gluons. We come back below.

To probe  $CP$  asymmetries with accuracy BESIII can calibrate with transitions where  $CP$  asymmetries cannot happen. We have two examples with broad resonances, where the situations are ‘complex’:  $J/\psi \rightarrow \bar{N}(1440)N(1440)$  with  $\Gamma_{N(1440)} \sim (250 - 450)$  MeV carrying isospin  $I = 1/2$  and  $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1223)$  with  $\Gamma_{\Delta(1232)} \sim 117$  MeV carrying isospin  $I = 3/2$ . The BES experiment has measured the background very well and continue to do it. The total background is very small, which provides good opportunity for a clean probe of CPV signal.

From the knowledge of the previous BES measurement [14] (the main background channels are also listed in this

<sup>4</sup> In a  $p\bar{p}$  machine, the term  $\alpha_\Lambda$  and  $\alpha_{\bar{\Lambda}}$  can be separated alone [24].



reference) and the ongoing one [26], one conservatively estimates number of the combinatorial background events is roughly  $10^{-3}$  of the signal events, a very small fraction such that the CPV can be cleanly probed. That is one of the strengths of the BESIII collaboration. We can show this more transparently with an example. Till 2018 one expects  $2.6 \times 10^6$  signal events, and assuming the CPV is on the level of  $10^{-4}$  one has  $\Delta N = N_+ - N_- = 260$ . The background can induce  $\Delta N_{\text{bkg}} = \sqrt{2.6 \times 10^3} \approx 51$ . This illustrates that the nonzero  $A_T$  will really indicate the observation of a  $CP$  asymmetry. On the other hand, if the CPV  $A_T$  is below the level of  $10^{-5}$ , the impact of the background is important.

$$\text{D. } J/\psi \rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$$

Above we have talked about  $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1232)$  as background for  $J/\psi \rightarrow \bar{\Lambda}\Lambda$ . We had said before it is very important to analyze pairs of baryons. However the situation here is even more ‘complex’, as we have discussed just above:

- $\Sigma^+$  carries isospin  $(I, I_3) = (1, +1)$ , while  $\Lambda$  isospin zero.
- Looking on straightforward diagrams we get  $J/\psi \rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$  vs.  $J/\psi \rightarrow \bar{\Delta}(1232)\Delta(1232) \rightarrow \bar{p}p p\pi$  as a background.
- However, we have to go beyond that as you can see by comparing  $M(\Sigma^+) \simeq 1189$  MeV vs.  $M(\Delta(1232)) \simeq 1232$  MeV with the width of  $\Delta(1232) \simeq 117$  MeV. *Off-shell* intermediate amplitudes sizably affect total amplitudes and also measurable CP asymmetries in  $[\bar{p}\pi^0][p\pi^0]$  final states.

To say it with different words, but with the same meaning: there would be a sizable overlaps between the waves of  $\bar{\Sigma}/\Sigma$  and  $\bar{\Delta}(1232)/\Delta(1232)$  due to  $\Gamma(\Delta(1232))$ . Therefore we cannot ignore that.

- Therefore we use two different diagrams for transitions: “ $\Rightarrow$ ” describes the amplitudes due to QCD( $\times$ QED) that conserve P & C symmetries; “ $\rightarrow$ ” includes  $SU(2)_L$  with weak dynamics including sources of P, C and CP asymmetries. The direct ‘road’ is

$$J/\psi \Rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0], \quad (22)$$

while also a somewhat indirect one can happen due to off-shell intermediate amplitudes:

$$J/\psi \Rightarrow \bar{\Delta}(1232)\Delta(1232) \Rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]. \quad (23)$$

As said before, the impact of re-scattering is ‘complex’, as one can see from comparing  $\text{BR}(\Sigma^+ \rightarrow p\pi^0) \simeq 0.52$  &  $\text{BR}(\Sigma^+ \rightarrow n\pi^+) \simeq 0.48$  vs.  $\text{BR}(\Lambda \rightarrow p\pi^-) \simeq 0.64$  &  $\text{BR}(\Lambda \rightarrow n\pi^0) \simeq 0.36$ .

- There is another possible amplitude that is even more ‘complex’, in particular with

$$J/\psi \Rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow \bar{\Delta}(1232)\Delta(1232) \Rightarrow [\bar{p}\pi^0][p\pi^0]. \quad (24)$$

We ‘paint’ off-line exchanges of kaons or new dynamics.

The data produced by 2018 will be analyzed by the BESIII collaboration with the best tools. It is possible that off-line resonances like  $\bar{\Delta}(1232)\Delta(1232)$  might have an impact on CP asymmetries more on  $J/\psi \rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$  than in  $J/\psi \rightarrow \bar{\Lambda}\Lambda \rightarrow [\bar{p}\pi^+][p\pi^-]$ , since off-shell  $\bar{\Delta}(1232)\Delta(1232)$  are closer to the on-shell  $\bar{\Sigma}^- \Sigma^+$ ; the second vertex technique will help much to distinguish them from the background from  $\bar{\Delta}(1232)\Delta(1232)$ .

Using  $10^{10} J/\psi$  data that will be collected by the BESIII until end of 2018, we expect  $2.5 \times 10^6$  signal events, with sensitivity at 0.06%, see Table I.

$$\text{E. } J/\psi \rightarrow \bar{\Xi}^- \Xi^+ \rightarrow [\bar{\Lambda}\pi][\Lambda\pi]$$

It is also interesting to probe  $CP$  violation by using the decays  $J/\psi \rightarrow \bar{\Xi}^+ \Xi^-$  and  $\bar{\Xi}^0 \Xi^0$ . One can reconstruct both  $\Xi$ s in the  $\Xi \rightarrow \Lambda\pi$  mode. For the neutral channel  $\Xi \rightarrow \Lambda\pi^0$ , the  $\pi^0$  in  $\bar{\Xi}^0$  decay can be easily separated from that in  $\Xi^0$  decay without ambiguity, since both  $\Xi$ s are back to back and strongly boosted in the rest frame of  $J/\psi$ , namely, the  $\Xi^0 \rightarrow \Lambda\pi^0$  is reconstructed in the opposite decay hemisphere against the decay hemisphere for the  $\bar{\Xi} \rightarrow \bar{\Lambda}\pi^0$ . This situation will be similar as in Sec. for  $J/\psi \rightarrow \bar{\Sigma}^- \Sigma^+ \rightarrow [\bar{p}\pi^0][p\pi^0]$ . By 2018 we will have data for  $J/\psi \rightarrow \bar{\Xi}^+ \Xi^- \rightarrow \bar{\Lambda}\pi^+ \Lambda\pi^-$  and  $\bar{\Xi}^0 \Xi^0 \rightarrow \bar{\Lambda}\pi^0 \Lambda\pi^0$  with the numbers of  $1.1 \times 10^6$  and  $1.6 \times 10^6$  [15], respectively. Thus, the reaches for the triple-product asymmetry are about  $10 \times 10^{-4}$  and  $8 \times 10^{-4}$  for the charged and neutral  $\Xi$ , respectively.

Once non-zero values for CP asymmetries are found, one can attract another challenge: is it source of the transition of  $\Xi \rightarrow \Lambda\pi$  or  $\Lambda \rightarrow p\pi^-$  – or the interferences between them?

$$\text{F. } J/\psi \rightarrow \Lambda \bar{X} \text{ vs. } J/\psi \rightarrow \bar{\Lambda} X$$

One can also compare the transitions  $J/\psi \rightarrow \Lambda \bar{X}$  vs.  $J/\psi \rightarrow \bar{\Lambda} X$ , in particular  $J/\psi \rightarrow \Lambda \bar{p}K^+$  vs.  $J/\psi \rightarrow \bar{\Lambda} pK^-$ . 2016 data tell us:  $\text{BR}(J/\psi \rightarrow \Lambda \bar{p}K^+ / \bar{\Lambda} pK^-) = (0.89 \pm 0.16) \cdot 10^{-3}$ . By 2018 the expected number of events is about  $9 \times 10^6$  which has sensitivity for CP asymmetry of  $2.4 \times 10^{-4}$  by comparing the partial widths between  $J/\psi \rightarrow \Lambda \bar{X}$  and  $J/\psi \rightarrow \bar{\Lambda} X$  decays. The systematic uncertainty are expected larger than in the previous cases discussed above, but not by an order of ten.

### G. Summary from the experimental side

We learn about non-perturbative QCD with a novel situation; it is not trivial how much to apply them and where. Just below we give comments about available theoretical tools. The hope is to find signs of CP asymmetries in the decays of strange baryons; therefore the goal is not go for accuracy. We ‘paint’ the landscape to find CP asymmetries. Once our community has found non-zero value somewhere, one can discuss the correlations with other situations.

### III. COMMENTS ABOUT TOOLS FOR CP ASYMMETRIES

The realistic goal is to get new lessons about non-perturbative QCD; one can *hope* to find CP asymmetries in the decays of strange baryons; one can also dream to find the impact of ND [9]. When one goes after accuracy, one needs truly consistent parametrization of the CKM matrix [27]. However, that is not the goal now; therefore one can use the well-known Wolfenstein’s parametrization.

We have *local* operators for  $\Delta S = 1$  amplitudes. One describes the scattering of left-handed quarks  $s_L + u_L \rightarrow d_L + u_l$  with re-fined tree amplitudes and *local* penguin operators. Challenges come from true strong dynamics in different ways. In particular  $\mu \sim 1.0$  GeV describe the “fuzzy” boundaries between perturbative and non-perturbative QCD. On the other side the landscape is also complex, since the baryons carry spin-1/2; therefore there are more observables. To use different words, but the same substance: the amplitudes can be described with S- or P-waves.

There is another challenge, namely to connect quark and hadronic amplitudes. Namely, the item of “duality” is well known, and it is not just another assumption based on true quantum field theory. However, it does not work well, when one has to deal with thresholds that are important in these on-shell transitions  $J/\psi \rightarrow \bar{\Lambda}\Lambda$  and  $J/\psi \rightarrow \bar{\Sigma}^-\Sigma^+$ ; in these cases we have broad resonances like  $\Delta(1232)$  and  $N(1440)$ .

### IV. ABOUT THE FUTURE

As said above a realistic goal is to measure non-leptonic decays of  $\Lambda$ ,  $\Sigma^+$  and  $\Xi$  with more data to learn new

lessons about non-perturbative QCD. One can hope to find CP asymmetries in BESIII data by the end of 2018 and maybe – maybe – find the impact of ND. Of course, we need much more data, but also powerful analyses to reach even the realistic goal. Here we have listed the directions, where more data should improve our understanding of fundamental dynamics, see the Tab. I. In a future super tau-charm factory [28–30], one will have an unprecedentedly high peak luminosity of  $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ , with  $10^{12} J/\psi$  data samples, 100 times as large as the ongoing BEPCII/BESIII, which will result in a decreasing of the (statistical) uncertainty by 10 times further.

We need more thinking in general and in particular to point out not to focus on one transition, but analyzing correlations in different transitions are important.

Analyzing  $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$  can also give us novel lessons about non-perturbative QCD and even to compare  $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+ \rightarrow \Lambda + \bar{X}$  vs.  $e^+e^- \rightarrow \bar{\Lambda}_c^-\Lambda_c^+ \rightarrow \bar{\Lambda} + X$ .

Finally we add a comment that one first sees it as a technical one: applying “dispersion relations” has a long history about nuclear physics, hadrodynamics and High-energy physics (HEP) and also other branches of physics. They are based on central statements of quantum field theory, while their results depend on low energy data with some ‘judgment’. If the 2018 data we have discussed above exist, there is a good chance to convince members of our community to work on that.

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